Marine resource reliance in the human populations of the Atacama Desert, northern Chile – a view from prehistory

Charlotte L. King[a*], Andrew R. Millard[b], Darren R. Gröcke[c], Vivien G. Standen[d], Bernardo T. Arriaza[d,e], Siân E. Halcrow[a]

[a] Department of Anatomy, University of Otago, Dunedin, Otago, New Zealand

[b] Department of Archaeology, Durham University, Durham, United Kingdom

[c] Department of Earth Sciences, Durham University, Durham, United Kingdom

[d] Departamento de Antropología, Universidad de Tarapacá, Arica, Chile

[e] Instituto de Alta Investigación, Universidad de Tarapacá, Arica, Chile

* Corresponding Author

Email: charlotte.king@otago.ac.nz

All coauthors made substantial contributions to, and have approved the submission of this manuscript. Lead author CLK was responsible for study design, with advice from SEH and ARM. CLK collected samples, with aid from BTA and VGS, who also provided contextual information and insight into the regional archaeology. CLK undertook sample prep, samples were run by DRG, who wrote the analytical methods section of the manuscript. The bulk of the manuscript was written by CLK, with editorial input and suggested rewrites from all other co-authors.

Abstract

The Atacama Desert is one of the most inhospitable terrestrial environments on Earth, yet the upwelling of the Humboldt Current off the coast has resulted in the presence of a rich marine biota. It is this marine environment which first enabled the human settlement of the northern Atacama Desert, and continues to form the basis of regional economies today. In this paper we explore how the desert has shaped human dietary choices throughout prehistory, using carbon and nitrogen isotope analysis of human bone collagen (n=80) to reconstruct the diets of the inhabitants of the Arica region of the northern Atacama. This area is one of the driest parts of the desert, but has been generally understudied in terms of dietary adaptation. Statistical analysis using FRUITS has allowed deconvolution of isotopic signals to create dietary reconstructions and highlight the continued importance of marine resources throughout the archaeological sequence. Location also appears to have played a role in dietary choices, with inland sites having 10-20% less calories from marine foods than coastal sites. We also highlight evidence for the increasing importance of maize consumption, coinciding with contact with highland polities. In all periods apart from the earliest Archaic, however, there is significant variability between individuals in terms of dietary resource use. We conclude that marine resource use, and broad-spectrum economies persisted throughout prehistory. We interpret these results as reflecting a deliberate choice to retain dietary diversity as a buffer against resource instability.

Keywords: carbon; nitrogen; South America; dietary isotopes; FRUITS

1. Introduction

The Atacama Desert is one of the most extreme environments on Earth. As the driest hot desert in the world, life here is extremely marginal. Natural terrestrial resources are few, and freshwater availability is extremely limited (Williams et al., 2008). Human habitation of the desert, even today, is restricted to the valleys of the snowmelt-fed and seasonal rivers which traverse the Andean cordillera, and desert oases (Santoro et al., 2005). Yet, humans have occupied the desert for thousands of years (Arriaza et al., 2008). This is primarily due to the nearby marine environment. The Humboldt Current upwells off the north coast of Chile, bringing with it nutrient-rich waters and sustaining a rich and complex marine ecosystem (Thiel et al., 2007). The presence of plentiful marine resources meant that habitation of the desert was possible even prior to the adoption of agriculture, after which the ability to manipulate the desert environment began (Santoro et al., 2017).

In order to evaluate how different societies and natural environments affected diet in the Atacama Desert, however, there is a need for palaeodietary data from multiple parts of the desert, and different time periods. Palaeodietary work already undertaken in the Atacama Desert suggests, relatively unsurprisingly, that human subsistence choices were constrained by the desert environment (Santana-Sagredo et al., 2015; Torres-Rouff et al., 2012). There is evidence from the incipient agricultural sites (dating from 1700BC) of coastal valleys of extreme northern Chile, such as Pampa Tamarugal and the Loa River Valley, that during the transition to agriculture, desert populations retained significant marine-resource input into their diet (Bonilla et al., 2016; Pestle et al., 2015a; Santana-Sagredo et al., 2015; Torres-Rouff et al., 2012). This has been interpreted as reflecting the presence of trade networks (Pestle et al., 2015a; Pestle et al., 2015b) to mitigate the instability of terrestrial crops through use of marine resources (Santana-Sagredo et al., 2015). While trade networks developed during the Formative Period (*ca.* 1700BC - 450AD), these socio-economic interactions

continued during all subsequent periods, allowing some areas to become focused on maize agriculture and camelid pastoralism (e.g. Pestle et al., 2016; Torres-Rouff et al., 2015). Other regions seemed to have retained broad-spectrum based subsistence despite being influenced by polities whose dietary focus was maize (Knudson et al., 2007), such as the Tiwanaku, Wari (*ca.* 450–900AD) and later Inka peoples (1450–1600AD). These polities whose homelands were in the Peruvian highlands, expanded and annexed surrounding areas in the Middle Period (Wari and Tiwanaku) and Late Period (Inka). While there has, in the past, been a strong focus on the impact of these external polities and their reliance on maize in the Atacama Desert, it is becoming increasingly recognised that this crop has played a variable role in the subsistence economies of the desert people (Cuéllar, 2013; Tykot et al., 2006). Similarly, the role of different ecological niches in subsistence decisions is just beginning to be explored in the region (Zaro, 2007).

To date there have been relatively extensive isotopic studies of diet conducted in the San Pedro de Atacama and Tarapacá regions, but there is a dearth of data from the Arica region. These areas, while all located in the Atacama Desert, have quite different local environments, and therefore the potential for different subsistence choices in prehistory. For instance, the desert varies quite considerably in terms of freshwater availability and therefore suitability for human habitation and agriculture. In San Pedro de Atacama, in inland northern Chile for example, archaeological sites are centred around the natural oases. Agriculture was possible in this area (Llagostera and Costa, 1999; Nuñez, 2007) and it was likely an important stopping point for camelid traders moving from the political centres of the Andean highlands (Hubbe et al., 2012; Kolata, 1991; Llagostera, 1996). In Peru there are fog ‘oases’ in the desert, providing moisture which increases floral variability (Beresford-Jones et al., 2015) and the potential for agricultural yields (Sandweiss et al., 1999). The desert in the Tarapacá

and Arica regions, however is extremely dry, experiencing less than 0.6 mm of rain per year (Williams et al., 2008). Agriculture even today is possible in very restricted areas centering around the river valleys and inland oases.

As well as geographic variation in water availability, there has also been climatic variation in rainfall over time. The El Niño southern oscillation has serious effects on the amount of rainfall in any given year, and El Niño cycles have varied in intensity throughout prehistory (Gayo et al., 2012; Moseley and Keefer, 2008; Sandweiss et al., 2009). Around 500 BC, for example, palaeoclimatic data suggest a change to El Niño regime, resulting in higher levels of humidity in the Atacama Desert (Gayo et al., 2012), and considerably expanding the agriculture land available. During this time period archaeological evidence suggests the development of extensive field systems alongside villages such as Ramaditas, Guatacondo and Caserones (Uribe and Vidal, 2012; Vidal et al., 2012), located in harsh environments where today agriculture is not possible. In these sites, remains of *Zea mays*, *Phaseolus lunatus*, *P. Vulgaris*, Lagenaria, *Arachis hypogaea*, *Chenopodium quinoa* and Algarrabo (*Prosopis*) pods have been identified (McRostie et al., 2017; Santoro et al., 2017). These plants are not endemic to the northern Atacama and it is likely that they were introduced from the Andes and the eastern lowlands. This research aims to assess both the impact of the arrival of these crops, and the marginality of the desert environment on resource choices.

2. Environmental context: Arica region

The Arica region has four snowmelt-fed rivers, the Lluta, San Jose, Chaca and Camarones (Fig. 1). Further to the south it is more truly arid, with the Loa River and its tributaries

126 providing some of the only freshwater (Santoro, 2012). Use of the terrestrial environment in
127 the Arica region, however, is further complicated by the presence of high levels of
128 contaminating heavy metals (arsenic, lithium and boron) in the rivers (Apata et al., 2017;
129 Figueroa et al., 2012). This means that while there is freshwater, its use and consumption can
130 have serious health implications (Arriaza et al., 2010; Swift et al., 2015).
131
132 **Fig 1.** Location of the study area and surrounding regions. Inset gives study site locations and
133 occupation periods with the Azapa valley expanded for clarity.
134
135 Dietary adaptations in the Arica region have not yet been investigated using isotopic
136 techniques, but instead inferred using archaeological evidence. Archaeological evidence
137 suggests that marine resource consumption was fairly ubiquitous throughout prehistory, with
138 marine faunal remains and material culture associated with fishing found even in interior
139 valley sites (Table 1). From around 7000 BC the area played host to a large Archaic period
140 population of *Chinchorro* marine hunter-gatherers, who settled the coast and relied heavily
141 on the ocean for all sustenance (Arriaza et al., 2008; Standen et al., 2017). From 1700 BC,
142 however, there appears to have been a change in the El Niño regime, resulting in depression
143 of the fisheries, relocation of the coastal peoples into inland river valleys, and the beginnings
144 of agriculture in the region (Grosjean et al., 2007; Moreno et al., 2009; Williams et al., 2008).
145 The cultivation of the interior valleys will have provided the people of the region with the
146 ability to produce staple terrestrial crops for the first time. Andean domesticates such as
147 potato (*Solanum*), ullucu (*Ullucus*), and quinoa (*Chenopodium*) become common in the
148 archaeological record (Pearsall, 2008). Later in prehistory the region begins to interact with
149 highland Andean polities such as the Tiwanaku (Muñoz, 1983; Muñoz, 1995), eventually
150 being annexed by the Inka Empire in the Late Period (Santoro et al., 2010). These cultures

would have allowed resource trade with other parts of their empires, as well as having specific ideas surrounding diet. In particular, both the Tiwanaku people and the Inka Empire placed ceremonial importance on the consumption of maize (Goldstein, 2003; Staller, 2010). There is ethnographic and archaeological evidence that, despite the marginality of agricultural land, the area became significant for maize production under the Inka Empire (Murra, 1980; Santoro et al., 2010).

In this study we investigate the effect of the desert environment on prehistoric resource-use in the Arica region. We hypothesise that the marginality of the desert means that ancient populations are unlikely to have relied solely upon agricultural resources in any period. Instead a sustained reliance on marine resources is likely. The ocean has always been a plentiful source of food, leading to a maritime tradition which persists even into the present day. We therefore examined diet in coastal and near-coastal valley sites from both agricultural and pre-agricultural periods to examine whether or not dietary diversity, and marine resource use, is maintained throughout prehistory. We then compare the isotopic data to other lines of archaeological evidence relating to resource use to build a fuller picture of subsistence strategies in the region.

3. Archaeological context

The studied samples derive from archaeological sites in the northern Atacama Desert, close to the modern-day city of Arica (Fig. 1). Sites lie both on the coast, and in the near-coastal areas of the Azapa Valley. This region has a long human occupation history, but not all periods and cultures are present both inland and on the coast. For example, the Archaic period is not well-represented in the inland valleys. Conversely there is a lack of evidence for

176 Middle Period occupation of the coast (Muñoz, 1982; Sutter, 2000). The known prehistoric
177 cultural sequence is therefore briefly described here.
178
179 *Archaic Period:*
180 The first evidence for human settlement of the Arica region is between 9400–8200 BC
181 (Arriaza et al., 2008; Moreno et al., 2009), and corresponds with the presence of small
182 communities of hunters, fishers, and collectors well adapted to exploitation of the marine
183 ecosystem. Most bioarchaeological and archaeological evidence suggests that Chinchorro
184 populations were almost completely reliant upon the marine environment for subsistence
185 (Arriaza et al., 2017; Aufderheide et al., 1993). However, Holden (1994) and Reinhard et al.
186 (2011) have both reported possible cases of potato starch and quinoa seeds in Chinchorro
187 coprolites at Morro 1/6 site, suggesting the inhabitants harvested and consumed wild plants.
188 By 5000 BC these coastal populations developed extraordinary funerary practices including
189 artificial mummification that lasted until ca. 1500–1000 BC (Arriaza, 1995; Standen et al.,
190 2014; Standen, 2003). These dates mark the end of the Chinchorro cultural tradition and also
191 the transition towards food production in the coastal valleys of the Arica region (Grosjean et
192 al., 2007; Santoro et al., 2017).
193
194 *Formative Period:*
195 Although fisher-gatherer populations continue to live on the coast during the following
196 Formative Period, for example at the site of Quiani (ca. 1500–1600 BC), there is evidence
197 that plants such as squash and gourds were being incorporated into mortuary rituals. Recent
198 studies show there is a correlation between edible plants offered as grave goods in the
199 prehistoric sites of the Arica region, the species identified in human dental calculus (as
200 phytoliths and starch grains) and the frequency of dental caries (Arriaza et al., 2017).

Archaeological evidence suggests that later Formative Period coastal groups like Faldas del Morro (800 BC) had strong links to the inland valley sites and were incorporating agricultural products in their diet (e.g. (Belmonte, 1998; Erices, 1975).

There is however, much that remains unknown regarding the development of early farming cultures in the Arica region. While Formative coastal populations were incorporating agricultural products into their diets, it is probable that they maintained marine specialization, with terrestrial products forming only a very small portion of dietary intake. Indeed, most coastal sites are dominated by objects associated with maritime subsistence: hooks, harpoons, fishing lines, hook weights (Muñoz, 1993; Muñoz and Focacci, 1985). Inland sites also retain material culture associated with fishing, indicating that marine resources remained important (Santoro, 1980b). This is counter to traditional archaeological interpretations which have inferred that inland Formative sites are much more reliant upon agricultural resources.

The first farmers of the inland Azapa Valley sites have generally been associated with the Alto Ramírez cultural Phase, which according to Rivera (Rivera, 1994; Rivera, 1975) corresponds with a migration from the complex Formative centres of the highlands, such as Wankarane and Pukara down to the coastal valleys. This diffusionist model reflects archaeological paradigms which tended to try to establish cultural dependency between the marginal societies of the coastal valley in the Atacama Desert and the large power centers of the highlands. Although other studies (Muñoz, 2004; Núñez and Santoro, 2011) have highlighted the important and active role that local populations played during the Archaic-Formative transition, there must have been some exogenous contributions in this process. The first agricultural crops grown in the area are not endemic to the region and must have been brought in either through trade or movement of peoples or both. It is therefore possible that

the inland valley populations of the Arica region will have had a diet based upon terrestrial resources and buffered by exchange networks which extend to the highlands, as interpreted by Pestle et al. (2015a) further to the south.

Middle Period:

There is also debate in the archaeological literature over the extent to which the Arica region was involved in the expansion of highland polities (such as Tiwanaku and Wari) during the Middle Period. Traditionally the presence of Tiwanaku-style ceramics, particularly vessels (*queros*) used for the consumption of chicha (maize beer) has been used as evidence for these sites coinciding with the Middle Period (AD 450–900). However, there has been debate over the level to which groups were influenced by these polities. In the Arica region two cultural groups seem to have been present; Maytas and Cubuza, with Cabuza groups more influenced by the Tiwanaku. In this study we focus on the Cabuza sites as representative of the Middle Period. However, recent radiocarbon-dating of mortuary offerings in some of these Cabuza sites, has revealed them to belong to the Late-Intermediate Period (AD 900–1450), rather than the earlier Middle Period (Korpisaari et al., 2014). It is possible that Tiwanaku presence and influence in the Arica area was the result of political collapse in the Bolivian highlands, and displacement of peoples into the Northern Chilean valleys, rather than deliberate annexation during the height of Tiwanaku power (Korpisaari et al., 2014). Nonetheless, the importance of maize in the Tiwanaku culture is often inferred to have had an impact in the sites of the Arica region (Muñoz, 1983).

Later periods:

The foundation of maize agriculture laid by the Middle Period polities is usually assumed to have been elaborated by cultural groups during the Late-Intermediate Period (AD 900–1450),

culminating in the ritualised maize consumption that characterises the Late Period and associated Inka state (AD 1450–1600)(Goldstein, 2003; Staller, 2010). The cultivation and consumption of chicha underlay most social and ritual transactions during the Inka period, and was symbolically associated with imperial power (Bauer, 1996; Goldstein, 2003; Staller, 2010).

Chronology of sites used in this study

The dating of sites in the Arica region has been conducted somewhat haphazardly, and sometimes more recent radiocarbon dates directly contradict earlier dates (Korpisaari et al., 2014; Muñoz, 2017; Sutter, 2005). It was not possible to take radiocarbon samples for this project, we therefore use a combination of existing radiocarbon data and artefactual evidence for cultural affinity to assign sites used to archaeological phase. For instance, we consider sites with Tiwanaku pottery as representing the Middle Period, because their subsistence regime is likely to have been affected by Tiwanaku cultural values, similarly sites with Inka influence (i.e. the Camarones sites) are likely to have been influenced by Inka maize-reliance.

Table 1 gives the sites used in this study, their assigned phase and the rationale for that assignment. The focus of this isotopic study, however, is not chronologically constraining differences in subsistence choices, but instead understanding how the desert environment affected resource use during prehistory as a whole. Our analysis and interpretation does not look at change through time, but instead considers differences between inland and coastal sites, and sites with evidence for interaction with highland polities and those without. Diversity in resource use, or lack thereof, within and between sites will give us insight into

resource-use choices regardless of chronological gaps and issues with the construction of cultural sequences.

[Table 1 near here]

4. Materials and Methods

Analysis of stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopic ratios from human collagen provide an insight into the diet of past human society. In particular, it is possible to differentiate marine from terrestrial resource use, the photosynthetic pathways of plant resources used, and the trophic level of food indicating meat consumption or the type of marine resources exploited (Ambrose and Norr, 1993; Schoeninger and DeNiro, 1984). Carbon isotopes are fractionated differently according to plant photosynthetic pathway (C_3 vs. C_4), with C_3 plants favouring fixation of lighter ^{12}C more than C_4 plants do resulting in a more negative $\delta^{13}C$ value (Ambrose and Norr, 1993). In the Atacama Desert, crops such as quinoa, tubers and pulses (e.g. beans) are C_3 crops, and are differentiable from the C_4 crop, maize (which is less ^{12}C-enriched). Carbon isotopes may also be used to highlight marine resources, with marine carbonate concentrating ^{13}C, resulting in less negative $\delta^{13}C$ values in in comparison to C_3 plants (Chisholm et al., 1982).

Nitrogen isotopic ratios vary with trophic level, and each step up the food chain increases $\delta^{15}N$ values between 2‰ and 6‰ (DeNiro and Epstein, 1981; O'Connell et al., 2012). This means that broadly speaking, in the absence of aquatic resource consumption, $\delta^{15}N$ values can be related to levels of terrestrial meat consumption. However, as marine food-chains tend to involve more steps, consumption of high trophic level marine resources results in especially high $\delta^{15}N$ values (Fry, 2006; Minagawa and Wada, 1984). $\delta^{15}N$ values in Atacama

Desert terrestrial foodchains are also enriched in ^{15}N relative to other areas of the world (Díaz et al., 2016). This is a result of the aridity of the environment and resulting differences in nitrogen cycling (Ehleringer et al., 1992). Arid conditions result in the volatilisation of nitrogen compounds such as ammonia and this process preferentially involves the light isotope ^{14}N, thus concentrating ^{15}N in soils and foliage (Amundson et al., 2003), an enrichment which is carried through terrestrial food-chains (Gröcke et al., 1997; Hartman, 2011).

4.1 Materials

This study involved the sampling and isotopic analysis of adult individuals from the archaeological collections of the Museo Arqueológico San Miguel de Azapa (MASMA), Arica. The samples derive from the archaeological sites of the Azapa and Camarones river valleys, and the coastal sites of Arica (Fig. 1). Sites and numbers of individuals sampled are listed on Table 1, a complete list of individuals sampled is given in Table S1. MASMA enforces strict sampling regulations to preserve their collections. The sampling of bone was therefore restricted to 25 adult individuals from each phase. Collagen was assessed using Durham University Archaeology laboratory protocols and was considered to be of good quality if: C/N ratio = 2.9–3.6 and 35–50% carbon and 11–16% nitrogen (e.g. (DeNiro, 1985). A number (n = 13) of individuals from the Archaic phase sampled had poor preservation of collagen, with the collagen extracted not passing standard quality control checks (see S1 Table). After excluding those with poor quality collagen the analysed sample set comprised of 80 individuals. The poor preservation of collagen in the Archaic samples has been previously documented in this region (Aufderheide et al., 1993; Silva-Pinto et al., 2014), and persists despite repeat preparation procedures and addition of a filtration step to the protocol. Sampling was restricted to individuals who were not artificially mummified,

ensuring that some bone was exposed and available for analysis. Only adults were sampled in this study to ensure all individuals were completely weaned and the isotopic signatures represent an adult diet. This work on adult diet, however, will form an important baseline for future work looking at infant diet and weaning patterns.

4.2 Methods

Skeletal sex estimation was undertaken by the authors [CK and VS] using the standards in Buikstra and Ubelaker (1994). Individuals were assigned to age groups (Young, Middle, Old) using standard scoring of the pubic symphysis (Brooks and Suchey, 1990) and auricular surface (Lovejoy et al., 1985), with epiphyseal fusion taken into account in the case of young adults (Buikstra and Ubelaker, 1994).

Samples of bone weighing between 100–200 mg were taken using a diamond cutting wheel. These were removed from already fragmented and disarticulated ribs to avoid unnecessary damage to any skeletal elements or mummified material. Adhering particulates were removed through surface abrasion with a diamond burr. Prior to collagen extraction a defatting procedure equivalent to those used in analysis of modern bone was employed (O'Connell et al., 2001). The samples were rinsed in deionised water then sonicated in test tubes containing a 2:1 methanol:chloroform solution for 2 hours, with the solvent changed every 30 minutes. Bone fragments were then prepared following a modified Longin (Longin, 1971) method i.e. demineralised in 0.5M HCl, gelatinised in a pH3 HCl solution at 75°C overnight, centrifuged and decanted to remove particulates, then lyophilised.

Total organic carbon, total nitrogen content and stable isotope analysis of the samples was performed using a Costech Elemental Analyser (ECS 4010) connected to a Thermo Delta V Advantage isotope ratio mass spectrometer. Carbon isotope ratios were corrected for ^{17}O

contribution and reported in standard delta (δ) notation in per mil (‰) relative to Vienna Pee Dee Belemnite (VPDB). Isotopic accuracy was monitored through routine analyses of in-house standards, which were stringently calibrated against international standards (e.g., USGS 40, USGS 24, IAEA 600, IAEA N1, IAEA N2): this provided a linear range for calibration in $\delta^{13}C$ between –46.7 ‰ and +2.9 ‰ and in $\delta^{15}N$ between –4.5 ‰ and +20.4 ‰. Analytical uncertainty in carbon and nitrogen isotope analysis was typically ±0.1 ‰ for replicate analyses of the international standards and typically <0.2 ‰ on replicate sample analysis (see S1 Table). Total organic carbon and nitrogen data were obtained as part of the isotopic analysis using an internal standard (Glutamic Acid, 40.82 % C, 9.52 % N).

The statistical software R (R core team, 2013) was used to script and visualise our data. In an effort to increase the reproducibility of research (Marwick, 2017) .csv files and R scripts used in this analysis have been made available via a GitHub repository (https://github.com/DrCharlieKing/Atacama_Bulk). Values from modern terrestrial flora and fauna data were corrected for the Suess effect to pre-industrial levels (Long et al., 2005) using data from Francey et al. (1999). There is also a systematic offset between human collagen values and those of the diet consumed. When presenting human data with foodweb data this dietary offset is corrected for by shifting human values to those of their diet, to allow easier visualisation of possible dietary components. There is debate over the exact magnitude of this offset (O'Connell et al., 2012), but here we use controlled feeding data and consider the $\delta^{13}C$ diet-collagen offset as 4.8 ± 0.5 ‰, and $\delta^{15}N$ diet-collagen offset as 5.5 ± 0.5 ‰ (Fernandes et al., 2012; Froehle et al., 2010; Huelsemann et al., 2009).

In the Atacama Desert there are a number of resources that overlap substantially in terms of isotopic signatures, for example less negative $\delta^{13}C$ values may represent C_4 crop or marine

resource consumption. Although analysis of dental enamel carbonate ($\delta^{13}C_{apatite}$) could potentially resolve these interpretive issues, sampling restrictions prevented this being undertaken as a part of this study. Instead, quantitative dietary reconstruction was undertaken using a Bayesian mixing model – Food Reconstruction Using Isotopic Transferred Signals (FRUITS) (Fernandes et al., 2014), in order to account to some extent for dietary routing and offsets.

FRUITS allows the estimation of the contribution of different food sources to the diet using measured isotopic values and food source data (Fernandes et al., 2014). It takes into account dietary routing (i.e. the preferential use of certain dietary components in specific tissues) and isotopic offsets, and allows the incorporation of *a priori* assumptions. In this study we used a weighted and concentration-dependant model, considering the input of both the protein and energy components of the diet in the consumer isotopic values. The main FRUITS model used is given as Supplementary File 1. Mean values for each of the phases were used to model group diet, although we also present results from individuals to demonstrate the heterogeneity in diet within single sites. We considered the input of four dietary sources: C_3 plants, C_4 plants, terrestrial meat and marine meat (including shellfish, fish and marine mammals). Food source values were derived from previously conducted isotopic work in the Northern Atacama (Cadwallader et al., 2012; DeNiro and Hastorf, 1985; Szpak et al., 2012; Tieszen and Chapman, 1992) that is summarised in Andrade et al. (2015). Weighting of the model was based upon previous work detailing average nutrient contribution of the different food groups to human diet (Fernandes et al., 2015), with plant cereals protein: 10 ± 2.5 wtC %; carbs/lipids: 90 ± 2.5 wtC %, terrestrial meat sources: 30 ± 2.5 wtC %; carbs/lipids: 70 ± 2.5 wtC % and marine foods: 35 ± 5 wtC %; carbs/lipids: 65 ± 5 wtC %. We also follow Fernandes et al. (Fernandes et al., 2015; Fernandes et al., 2014) in using the *a priori*

assumption that overall dietary protein intake will involve protein carbon contribution of between 5–45 % (Otten et al., 2006). In addition, the Archaic Period reconstructions included the prior that C_4 resources form the least important component of diet, as there are no endemic C_4 resources in the Arica region, and therefore it is not until the Formative Period that we would expect these to become a possible important component of diet. Isotopic offsets were defined using the same controlled-feeding experiment data as used to plot our data ($\delta^{13}C$ diet-collagen offset = 4.8 ± 0.5 ‰, $\delta^{15}N$ diet-collagen offset = 5.5 ± 0.5 ‰) (Fernandes et al., 2012; Froehle et al., 2010; Huelsemann et al., 2009).

To test the robustness of dietary reconstructions alternative models using different dietary information and parameters were also run, and their results compared to our primary model. The first of the alternative dietary scenarios involved the inclusion of fertilised C_4 plant data (see Supplementary File 2). The fertilization of maize with seabird guano was a common agricultural practice during the Late Period (Julien, 1985), and results in elevated $\delta^{15}N$ values, such that fertilised maize overlaps isotopically with high trophic level marine resources (i.e. marine carnivores such as sealions). In our model we have considered guano fertilization a possibility from the Middle Horizon onwards, as the earliest archaeological evidence for potential deliberate use of guano is from this period (Kelley et al., 1991; Muñoz and Focacci, 1985). The inclusion of this data in our model allows us to quantify the potential confounding effects of fertilization on our data. In addition, three other model types were run: 1) removing *a priori* assumptions (Supplementary File 3); 2) with offsets altered by ± 1 ‰ (Supplementary Files 4 and 5); and 3) with food values altered by ± 1.5 ‰ (Supplementary Files 6-9). Dietary reconstructions are considered robust if these changing parameters did not result in significant changes to dietary contribution estimates.

5. Results

The results of carbon and nitrogen isotopic analysis are given with reference to local foodweb data in Fig. 2, and are reported in full in Table S1.

Fig. 2: Isotopic baseline data plotted alongside average human dietary values for each phase (with 95% confidence ellipses). Human isotopic values have been corrected for the diet-tissue offset (as described in-text). Datapoints represented by squares (rather than circles) are individuals representing the 'extremes' of dietary variation in each phase. These individuals have associated individual FRUITS dietary reconstructions (Fig. 4).

5.1 FRUITS dietary estimates

Fig. 3 presents the dietary reconstructions generated by our main FRUITS model for each for each archaeological period. The estimated contributions of each food source, and uncertainties associated with these estimates are also given in Table 2.

Fig. 3: FRUITS model output for each archaeological phase. Box and whisker plots (left) represent credibility intervals, with boxes representing a 68% credible interval, and whiskers a 95% credible interval. Horizontal lines represent the mean and median (dashed and continuous lines respectively). Probability distributions (right hand figures, y-axes) are given for each of the contribution estimates (x-axes).

[Table 2 near here]

As Fig. 2 and high standard deviations in Table 2 show, there are relatively high levels of dietary variability in each of the phases. We acknowledge that the individuals grouped in archaeological phases may not be contemporaneous and therefore directly comparable due to the long occupation period of some sites. To fully describe the variation present, even within one site, we have generated FRUITS estimates of dietary contributions for individuals representing the extremes of diet in each phase (individuals marked as squares on Fig. 2). The Archaic Period is excluded from this individual analysis due to the small sample size and relative homogeneity of diet in this phase.

These individual results are presented in Fig. 4 and Table 3.

[Table 3 near here]

Fig. 4: FRUITS model output for each archaeological phase. Boxes represent 68% credible intervals, and whiskers 95% credible intervals. Horizontal lines represent the mean and median (dashed and continuous lines respectively).

5.2 Robustness and accuracy of dietary estimates

The dietary inputs calculated by the alternative models are given in supplementary tables S2-4. Each of the modelled dietary scenarios have similar probability distributions associated with different food sources (% input), although the actual percentages vary with the changing model parameters. Each dietary scenario has associated uncertainties ranging between 2 and 20 %, with the majority of uncertainties being under 15 %. These uncertainties are not large

467 enough to change the overall interpretation of which resources are contributing the most to
468 diet in each of our phases.
469
470 In most of the modelled dietary scenarios, despite the reconstructed % contributions to diet
471 changing, the overall reconstruction of which resources contribute more or less to diet
472 remains the same. For example, the Archaic estimates always show that marine food makes
473 up the majority of the diet, with C_4 resources comprising only a small portion. In the
474 Formative period it is terrestrial resources which make up the bulk of the diet, in particular C_3
475 plants. In the later phases C_4 plants form the foundation of the diet, although in the coastal
476 Late Period sites marine resources form an equally important portion. Interestingly the
477 inclusion of guano fertilised maize data (i.e. C_4 crops with significantly higher $\delta^{15}N$) from the
478 Middle Period onwards does not significantly affect model outcomes (S4 table). Estimated
479 dietary contributions in the guano-fertilised model differ by 2–6 % from the main model
480 presented in this paper.
481
482 The removal of prior assumptions from the model does significantly affect percent
483 contribution estimates in the Archaic, with a change to estimated C_4 contribution of 18 %.
484 Aside from large changes to the Archaic Period estimates when priors are removed, the
485 majority of other models run change the percent contribution estimates by no more than 6 %.
486 This extreme change in the Archaic is due to the removal of the prior assumption that C_4
487 resources will comprise the smallest contribution to diet, due to lack of endemic C_4 plants.
488 Other phases did not include this prior due to the presence of C_4 resources introduced from
489 the highlands.
490

491 # 6. Discussion

The results of analysis using FRUITS clearly support the hypothesis that marine resources remained an important dietary component throughout the prehistory of the Arica region. In addition, they highlight that proximity to the coast, perhaps unsurprisingly, has the most significant impact on the level to which marine resources are consumed, though they are a consumed in all sites regardless of time period or cultural affiliation. The arrival of maize and increasing importance of this resource from the Middle Period onwards is also visible isotopically. Here we discuss the persistence of marine resource use through time, the retention of broad-spectrum subsistence strategies and geographic constraints on resource use, and the possible influence of maize-reliant polities on subsistence in the region.

6.1 Continued consumption of marine resources despite the arrival of agricultural resources

The results of FRUITS analysis clearly indicate the continued consumption of marine resources throughout prehistory in the Arica region. In sites closest to the coast i.e. those from the Archaic and Late periods, marine resources provide around 40 % of caloric input, although some individuals within those sites appear to have had a marine input closer to 60 %. Most archaeological models assume the arrival of agriculture in the Formative Period involved an increase in terrestrial resource consumption, and this is borne out by our data which suggests that terrestrial resources do provide more caloric input during these periods. Marine resources, however, continue to comprise between 15–20 % of the diet. This aligns well with isotopic research in other parts of the Atacama Desert which has shown the persistence of marine resource use in both coastal and inland sites during the Formative Period (Andrade et al., 2015; Pestle et al., 2015a; Santana-Sagredo et al., 2015).

In addition, within each agricultural archaeological period analysed in this study there remains variation in marine resource consumption, with some individuals obtaining up to 68 % of their calories from the ocean (e.g. Az141 T10 in the Formative Period). This is a higher contribution even than the most extreme values from coastal sites in this study.

6.2 The importance of the environment – coastal vs. inland sites

In this sample over all periods and locations we see that resource decision-making is clearly affected by geographic availability, particularly relating to proximity to the coast. In our sample the sites located on the coast (i.e. the Archaic Morro sites and Late Period Camarones sites), unsurprisingly, consumed the most marine resources. There is no statistically significant difference in marine resource consumption between the Archaic and Late Period sites, but there are statistically significant differences between all inland (Formative, Middle and Late-Intermediate) sites and coastal (Archaic and Late) sites. This reflects the persistence of a marine tradition which is present even today in the modern cities of the coastal desert.

Inland sites, however, have approximately 20 % less caloric input from marine food sources than those at the coast. This is not necessarily as expected, as all sites analysed are within a day's walk from the coast, and marine resource gathering requires less energy input than rearing livestock or cultivating crops. There is, in addition, no correlation between absolute distance from the coast and marine input into the diet. Formative sites included in this study are the closest valley sites to the coast, yet display the least marine resource use. Middle Period sites analysed here are 10–15 km further from the coast, but use the most marine resources of all of the agricultural periods. Instead we consider it more likely that the inland

sites, in general used less marine resources but the specific amounts used will have been dependent upon climatic conditions affecting the fisheries. Prevailing archaeological models, for example, predict that the initial move inland during the Formative Period was precipitated to changes to El Niño intensity which dramatically depressed the fisheries (de Bryson et al., 2001; Muñoz and Chacama, 2012). It is perhaps unsurprising then that we see the least use of marine resources in these earliest agricultural sites. Climatic oscillations during site occupation may also be responsible for the high levels of 'within site/phase' variation in isotopic results we see. Small-scale variations in El Niño cycles are likely to have caused differences in the availability of resources throughout prehistory. Individuals within the same site may have experienced quite different resource pressures, even generation to generation, if water availability changed or marine upwelling was affected. Thus the variation in marine resource use may not have been personal choice or culturally-mediated, but instead environmentally-dictated.

6.3 The importance of maize and links to external polities

It has been generally assumed that maize played a more important role in subsistence from the Middle Period onwards, due to the presence of maize-reliant polities such as the Tiwanaku (Middle Period) and the Inka state (Late Period) (Goldstein, 2003). This does appear to be the case in the study sample, as C_4 contribution to the average diet increases dramatically between the Formative (24 %) and Middle Horizon (46 %), with C_4 contribution to diet remaining high throughout the subsequent archaeological phases. Even in coastal Late Period sites, where marine resources are likely to have been much easier to access, C_4 consumption provides a reasonable proportion of total caloric input (39 %).

567 However, it should be noted that maize consumption in the Arica region never reaches the
568 calculated levels of other areas annexed by or in contact with these same polities. For
569 example, in the Ayacucho Valley of Peru, dietary isotope analysis has suggest that maize
570 provided around 70% of dietary protein (Finucane, 2009). It is possible that the geographic
571 location of the Azapa Valley, away from major centres of Tiwanaku and Inka control, meant
572 that there was less cultural importance placed on maize consumption in this area (e.g. (King
573 et al., In review).
574
575 **6.4 Linking isotopic and archaeological evidence for subsistence strategies**
576
577 Overall the FRUITS reconstructions align well with archaeological evidence for subsistence.
578 The dietary reconstructions presented here, however, also go some way to resolving
579 archaeological questions about the importance of different resource types in each site. For
580 example, archaeozoological and material culture evidence for marine resource consumption
581 is present in all inland sites analysed (Focacci, 1990; Santoro, 1980a; Valenzuela et al.,
582 2015), but it is difficult to know how important these resources were. Our results show that
583 not only were marine resources present they also comprised an important part of the diet,
584 although the input into individuals' diet was variable.
585
586 The variety of crop species and subsistence tools found even at inland agricultural sites may
587 be used to infer that life in the Azapa Valley was never focussed on a single crop or
588 subsistence strategy (Muñoz, 1987; Valenzuela et al., 2015). Our isotopic results support this
589 interpretation, showing that the average diet during the Formative Period involved roughly
590 equal proportions of C_3 and C_4 plants, terrestrial meat and marine resources. Even extreme
591 individuals in this phase, who relied more upon one resource type than the others, still seem

592 to have been consuming small proportions of other resource types. There is archaeological
593 evidence for an increase in maize consumption in the Middle Horizon and Late-Intermediate
594 Periods in that maize remains and material culture associated with chicha consumption
595 become ubiquitous in sites (Muñoz and Focacci, 1985; Muñoz and Zalaquett, 2015). Our
596 isotopic results corroborate the idea that maize becomes more important, as in both the
597 Middle Horizon and Late-Intermediate periods C_4 resources are the most important dietary
598 component. They are not, however, solely relied upon, and indeed there are some individuals
599 for whom they form a much lesser proportion of the diet.
600
601 Archaeological research has previously questioned the importance of maize at Late Period
602 coastal sites despite Inka cultural involvement. At sites such as Camarones maize cannot be
603 grown locally and archaeobotanical evidence indicates that chicha (traditionally a maize
604 beer), appears to have been made primarily from C_3 crops rather than maize (Arriaza et al.,
605 2017; Arriaza et al., 2016). Our research indicates that maize is likely to have formed an
606 important component of the diet despite its lack of inclusion in chicha. In fact, the C_3 crops
607 from which chicha was apparently made do not generally contribute much to diet. It is
608 possible that the use of these crops in chicha was more an expression of local identity while
609 under Inka rule, than an indication of lack of maize availability.
610
611 **6.5 Variation in isotopic results, and diet in general, from each phase**
612
613 Isotopic results from the inland Formative, Middle and Late-Intermediate Periods are
614 extremely variable. Perhaps the most extreme example of this variation comes from
615 Formative Period Az14, where individuals at one extreme appear to be consuming almost
616 exclusively C_3 plants, while others seem to have a diet dominated by marine protein. It is

tempting to interpret this isotopic variation within archaeological phases or single sites as evidence for heterogeneous diet between contemporary individuals. Unfortunately, however, the ambiguity of site dating in the Arica region means that individuals within the same site are not necessarily contemporaneous. Instead, this variation may indicate generational changes to diet, perhaps reflecting cyclical resource availability due to El Niño oscillations, or cultural change resulting in the changing popularity of some resources. Future work involving the tightening of site chronologies may reveal systematic temporal changes to diet within phases, that are currently not interpretable.

6.6 Differences between FRUITS dietary reconstructions and previous modelling in the region

One of the major differences between the dietary reconstructions generated in this study and those attempted previously (Aufderheide et al., 1994; Aufderheide et al., 1993) is the percent input of marine resources estimated. The linear mixing models in these studies have predicted up to 80 % of dietary protein was derived from marine resource consumption. We anticipate that this difference is partly due to our use of Bayesian rather than simple linear mixing modelling, but is also because our FRUITS model used metabolic experimental data to define the acceptable intake of dietary protein. As a result of this our dietary reconstructions seem to align better with archaeological evidence for subsistence than earlier estimates. For example, while marine resources undoubtedly formed the most significant portion of Archaic diet there is evidence from Archaic coprolites of C_3 plants and terrestrial meat (Reinhard et al., 2011). Our dietary reconstructions support this idea of terrestrial resource use, and reduce estimates of percent contribution of marine resources to what we consider more reasonable levels.

7. Conclusion

The isotopic results presented here paint a picture of deliberate retention of dietary diversity in the peoples of the Atacama Desert. The marine resource use traditions begun by the Archaic *Chinchorro* peoples persist throughout prehistory and into the modern day, with use of the rich marine environment buffering the desert populations against terrestrial resource insecurities. While the arrival of maize-reliant polities does seem to have had an impact on subsistence in later archaeological phases, agricultural crops are never fully relied upon. Instead geographic constraints, such as proximity to the ocean, seem to have had a greater impact on overall diet. Our results also highlight dietary diversity both within and between archaeological phases, potentially relating to changes to resource availability and El Niño cycles.

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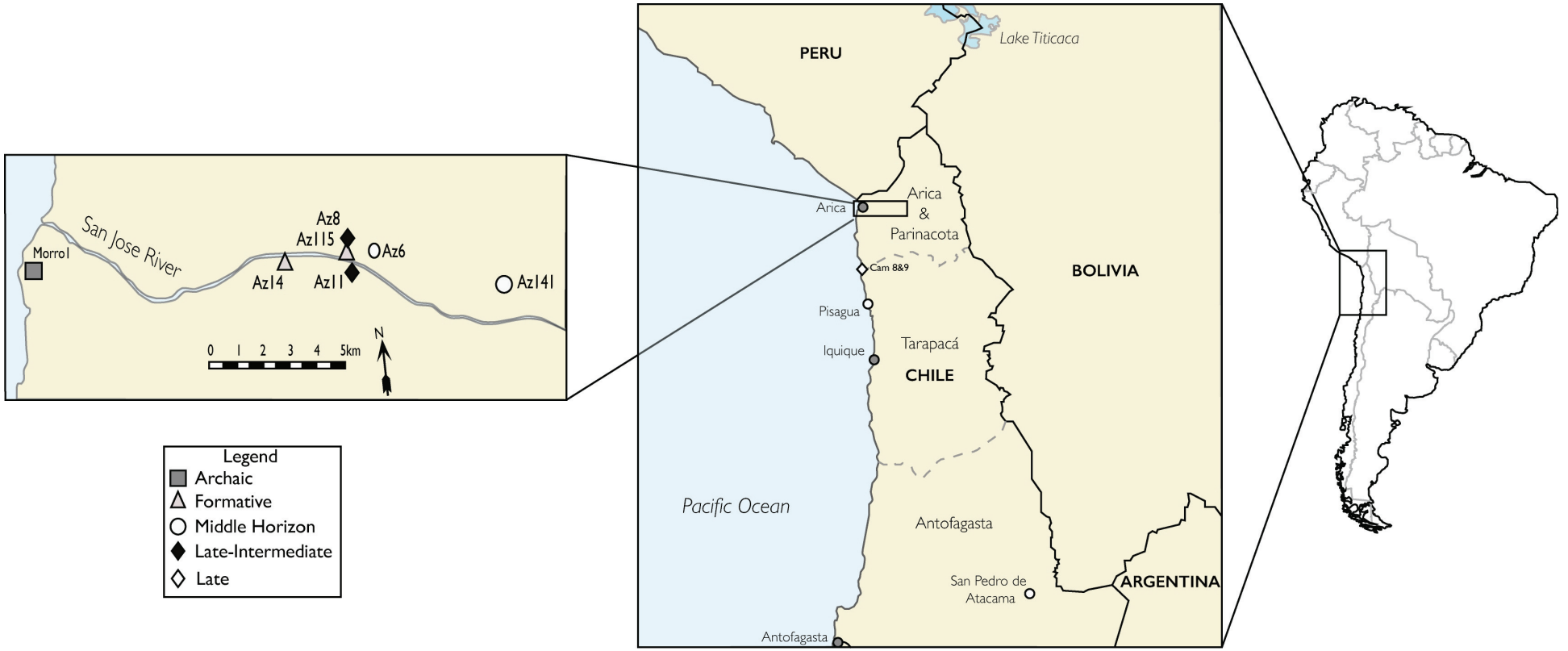
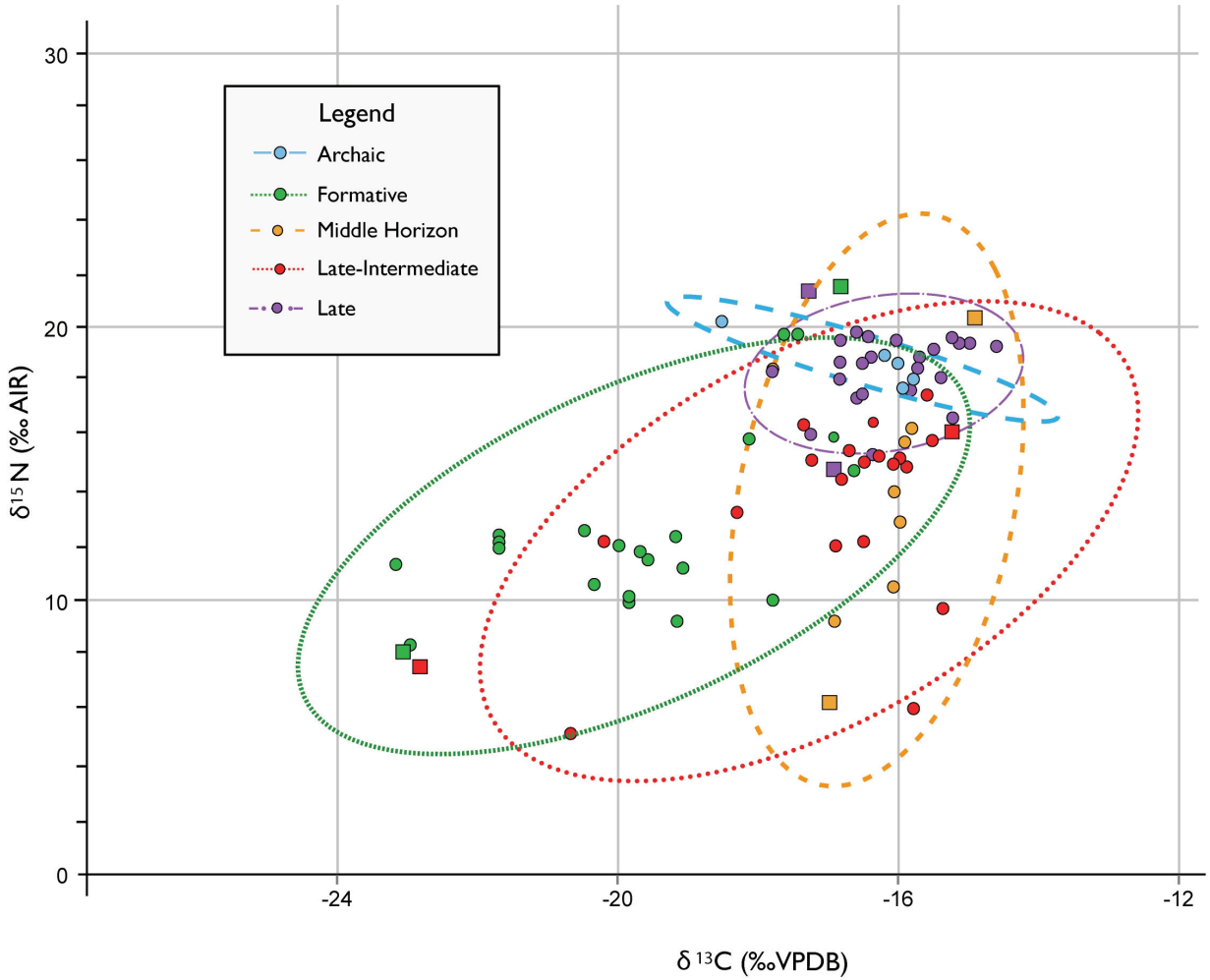
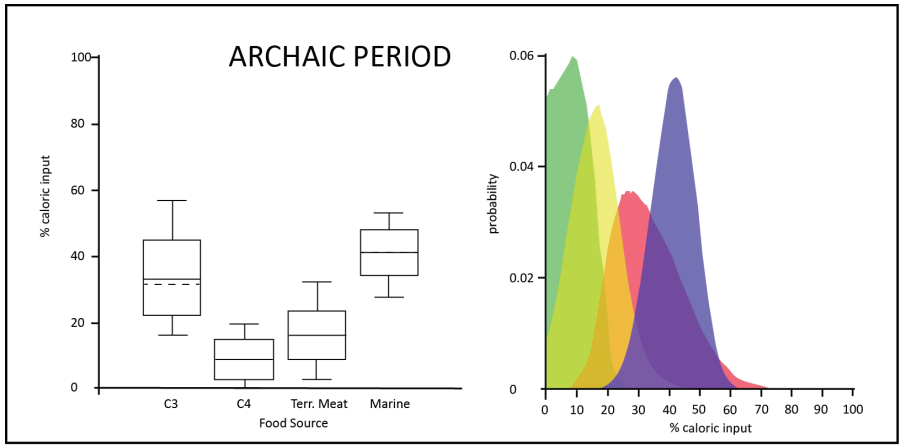
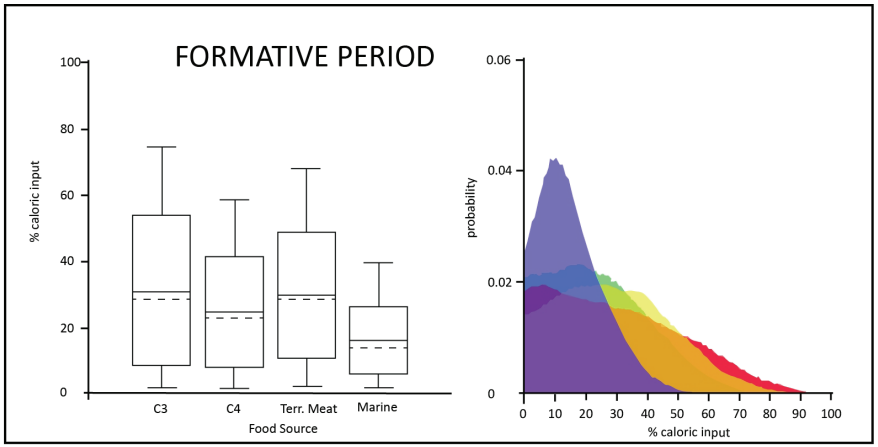
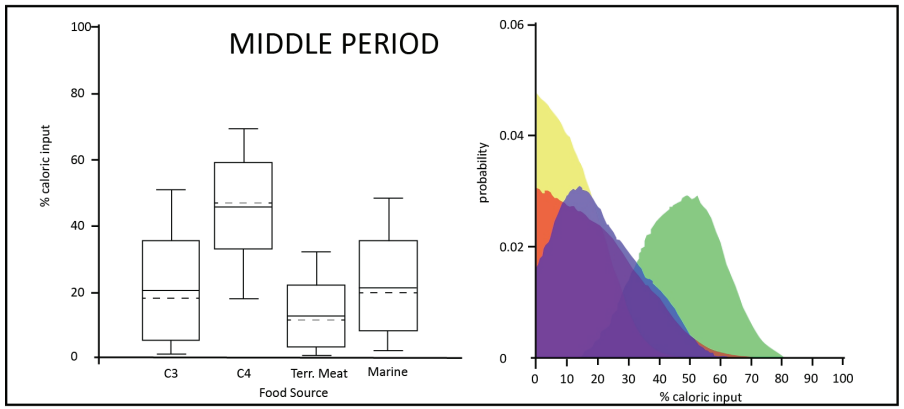
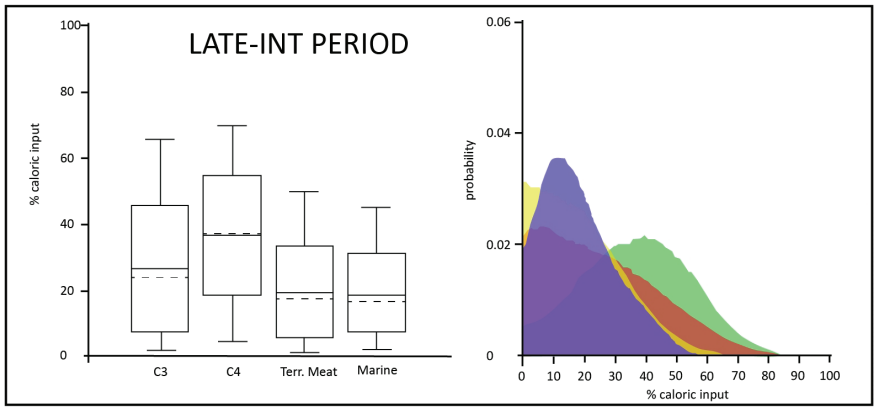

San Jose River
Morro1
Az8
Az115
Az6
Az14
Az11
Az141
0 1 2 3 4 5km
N
Legend
Archaic
Formative
Middle Horizon
Late-Intermediate
Late
PERU
Lake Titicaca
Arica
Arica & Parinacota
Cam 8&9
BOLIVIA
Pisagua
Iquique
Tarapacá
CHILE
Pacific Ocean
Antofagasta
San Pedro de Atacama
ARGENTINA
Antofagasta

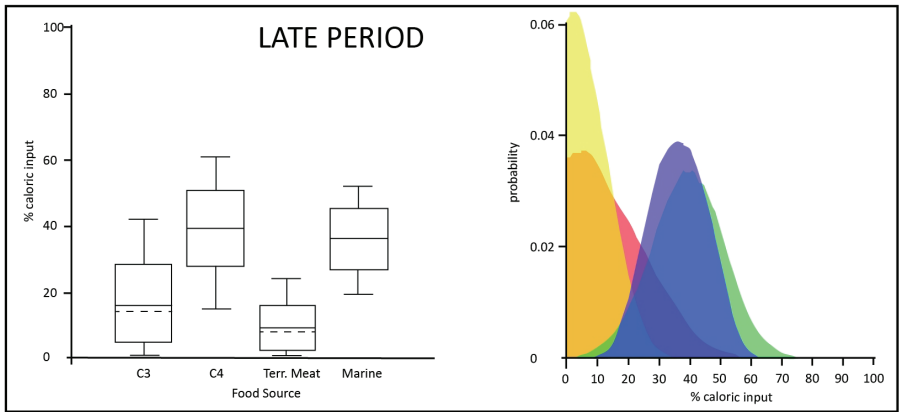

Legend
Archaic
Formative
Middle Horizon
Late-Intermediate
Late
30
20
10
0
-24
-20
-16
-12
δ15N (‰ AIR)
δ13C (‰VPDB)

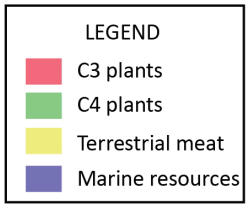

ARCHAIC PERIOD
% caloric input
Food Source
C3
C4
Terr. Meat
Marine
probability
% caloric input

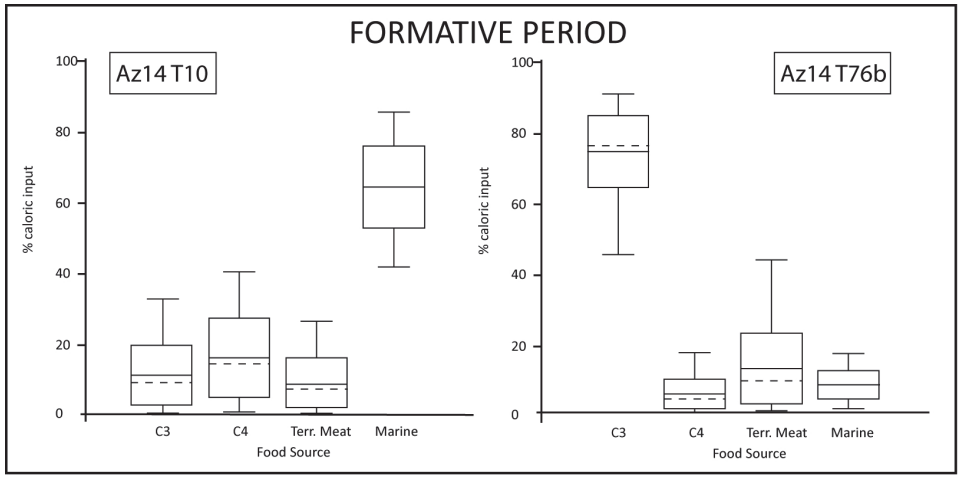

FORMATIVE PERIOD
% caloric input
Food Source
C3
C4
Terr. Meat
Marine
probability
% caloric input

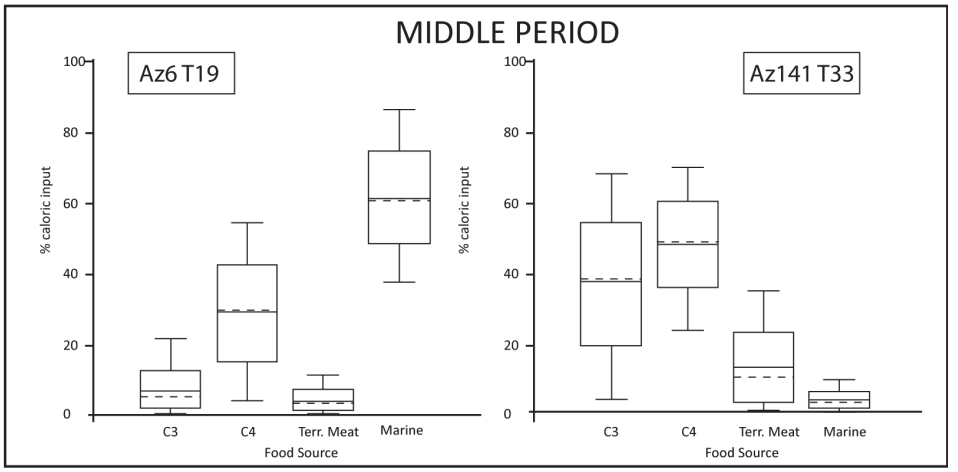

MIDDLE PERIOD
% caloric input
Food Source
C3
C4
Terr. Meat
Marine
probability
% caloric input

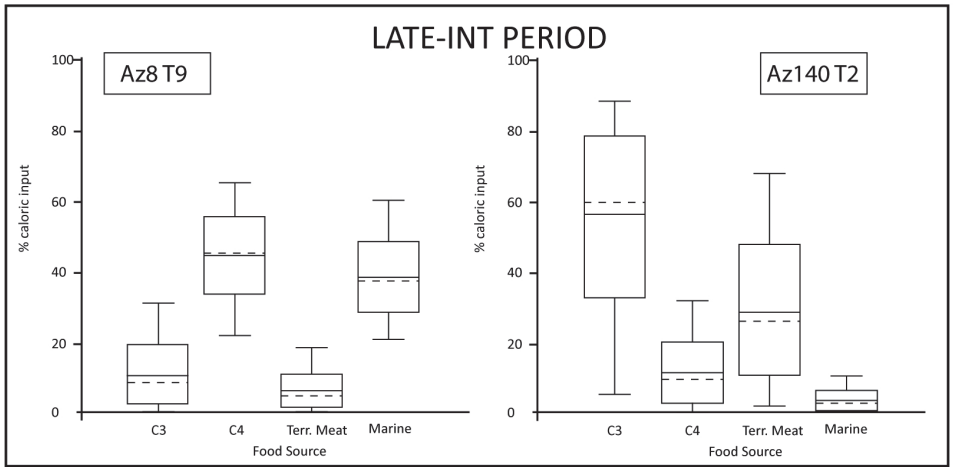

LATE-INT PERIOD
% caloric input
Food Source
C3
C4
Terr. Meat
Marine
probability
% caloric input

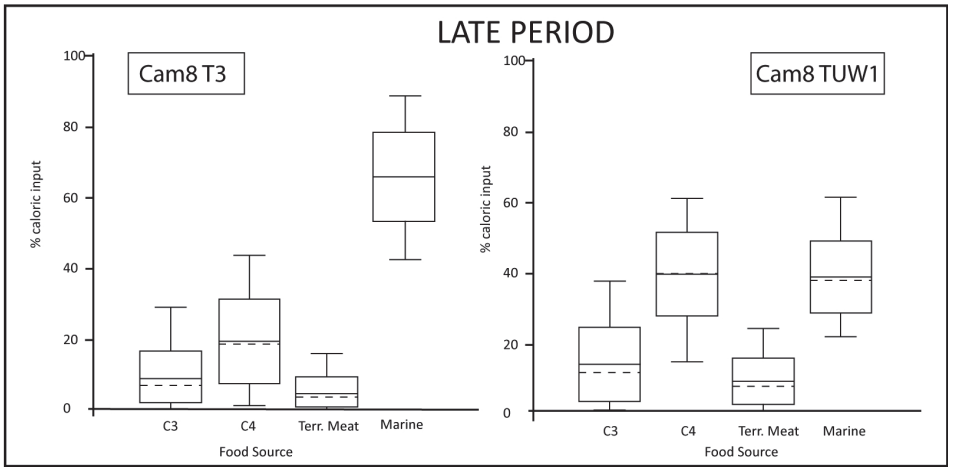

LATE PERIOD
% caloric input
Food Source
C3
C4
Terr. Meat
Marine
probability
% caloric input


LEGEND
C3 plants
C4 plants
Terrestrial meat
Marine resources


FORMATIVE PERIOD
Az14 T10
Az14 T76b
% caloric input
0
20
40
60
80
100
C3
C4
Terr. Meat
Marine
Food Source


MIDDLE PERIOD
Az6 T19
Az141 T33
% caloric input
0
20
40
60
80
100
C3
C4
Terr. Meat
Marine
Food Source


LATE-INT PERIOD
Az8 T9
Az140 T2
% caloric input
0
20
40
60
80
100
C3
C4
Terr. Meat
Marine
Food Source


LATE PERIOD
Cam8 T3
Cam8 TUW1
% caloric input
0
20
40
60
80
100
C3
C4
Terr. Meat
Marine
Food Source

	Archaeozoological/ botanical remains	Subsistence related material culture	Inferred subsistence strategy from archaeological evidence	Site dates (dating method)	Time period	Reason	Number of individuals sampled
Morro 1	Molluscs, crustaceans, seaweed, fish, marine mammals and birds, few camelid bones and skins (Standen, 2003). Plant fibre present in coprolites (Reinhard et al., 2011)	Harpoons, fishhooks, nets, ropes, 'chopes' (shellfish processing tools), spear, bows, darts, projectile points (Standen, 2003)	Marine hunter-gatherer	6226 – 1748 cal BC. (Allison et al., 1984) 2917 cal BC (Standen, 1991) (radiocarbon dates on burials)	Archaic	Radiocarbon dates.	5
Az115	Curcubita, maize, tubers camelids, dog, guinea pig, birds, fewer fish and marine mammal bones (Muñoz Ovalle, 2017)	Darts, spear tips, slings	Broad-spectrum agriculturalists	100-600AD (radiocarbon dates on burials)	Late Formative	Radiocarbon dates. Although some recent dates place some burials in the Middle Period (Muñoz Ovalle, 2017) there are no Tiwanaku cultural features.	14
Az14	Shellfish, fish, guinea pig, maize, quinoa,	Chopes, bows, wooden points,	Broad-spectrum agriculturalists	900-560BC uncalibrated	Formative	Radiocarbon dates	8

	manioc, camote (Santoro, 1980a)	harpoons (context uncertain)(Santoro, 1980a)		(Santoro, 1980b; Santoro, 1982)			
Az141				1044-1290 cal. AD (Korpisaari et al., 2014) 890+/- 100 AD (Schiappacasse et al., 1991) 1018-1276 AD (Sutter, 2005)	Middle Horizon – Late Intermediate	Both Tiwanaku and Cabuza pottery present.	5
Az6	Maize, camote, squashes, coca, dog, guinea pig, llama, shellfish/shells, birds (Focacci, 1990)	Wooden digging/tilling sticks, bows, arrows, quivers,	Agro-pastoralists	380 AD (Focacci, 1990) 890 – 1392AD (Focacci Aste, 1982) 850-1350 AD (Korpisaari et al., 2014)	Middle Horizon – Late Intermediate	Both Tiwanaku and Cabuza ceramics and other items of material culture present.	5
Az11	Camelids, dogs, guinea pigs, 1x monkey, birds, rodents, maize, beans, squashes, camote, manioc,	Arrowheads, darts, hoes, sticks, wooden shovels, harpoons,	Agro-pastoralists	790-980AD (Muñoz Ovalle and Focaccia, 1985)	Middle Horizon	Radiocarbon dates BUT Maytas pottery (not Tiwanaku)	5

	potato, quinoa, molluscs, fish, freshwater snails.	chopes, fishhooks.					
Az8				1,150 – 1,350AD (Rothhammer and Santoro, 2001) 910AD – 1120AD (Espoueys et al., 1995) 500-890AD(Núñez, 1976)	Late-Intermediate	Radiocarbon dates	13
Cam8	Maize, sweet potato, manioc, squash, beans, quinoa, camelids, dogs, fish, marine mammals (Muñoz, 1989)	Wooden shovels, harpoons, arrowheads	Marine subsistence complemented by agricultural crops	1050-1560AD (Thermoluminescance of potsherds) (Schiappacasse et al., 1991)	Late	Inka pottery, textiles	10
Cam9	Birds, sealions, sea turtle, fish, shellfish, camelids, maize, squashes (Ulloa et al., 2000)	Harpoons, bows, darts, oars, fishhooks,	Marine subsistence complemented by agricultural crops.	1050-1560AD (Thermoluminescance of potsherds) (Schiappacasse et al., 1991)	Late	Inka textiles (Ulloa et al., 2000)	15

Table 1: Sites sampled in this study, geographic location, archaeologically-inferred subsistence regime and assigned time period with reasoning and key primary data sources

Phase	**C_3 input**	**C_4 input**	**Terrestrial meat input**	**Marine input**
Archaic	32 ± 10	10 ± 5	17 ± 7	41 ± 6
Formative	31 ± 21	24 ± 16	30 ± 18	15 ± 10
Middle Horizon	20 ± 14	46 ± 13	13 ± 9	21 ± 13
Late-Intermediate	24 ± 17	38 ± 16	20 ± 14	18 ± 12
Late	16 ± 11	39 ± 12	9 ± 7	36 ± 9

Table 2: % total caloric contribution to diet of each food source as reconstructed by FRUITS analysis. Errors given are 1SD.

Time period	Individual	C_3 input	C_4 input	Terrestrial meat input	Marine input
Formative	Az14 T10	9 ± 7	16 ± 9	7 ± 6	68 ± 9
	Az14 T76b	83 ± 6	3 ± 2	6 ± 5	8 ± 3
Middle	Az6 T19	6 ± 5	29 ± 13	3 ± 2	62 ± 13
	Az141 T33	37 ± 17	48 ± 12	12 ± 10	3 ± 2
Late Intermediate	Az8 T9	7 ± 6	51 ± 7	4 ± 3	38 ± 7
	Az11 T16	63 ± 16	9 ± 6	25 ± 14	3 ± 2
Late	Cam9 T59	8 ± 6	23 ± 10	3 ± 2	66 ± 11
	Cam8 TUW1	10 ± 8	46 ± 8	7 ± 4	37 ± 8

Table 3: % total caloric contribution to diet of each food source for selected individuals, as reconstructed by FRUITS analysis. Errors given are 1SD.

Sample	period	Sex	Age	C/N	C wt %	$\delta^{13}C$ (‰ PDB)	N wt %	$\delta^{15}N$ (‰ AIR)
M1 T3	**Archaic**	**F?**	**old?**	**3.8**	**33.7**	**-12.4**	**10.2**	**24.5**
M1 T4	Archaic	M	young	3.4	45.0	-11.1	15.4	23.4
M1 T6	Archaic	U	U	3.5	45.6	-11.2	15.2	23.1
M1 T7	**Archaic**	**M**	**U**	**4.0**	**31.9**	**-14.6**	**9.8**	**28.3**
M1 T10a	Archaic	M	mid	3.4	42.5	-11.5	14.6	24.3
MI T12	Archaic	M	young	3.4	37.4	-11.3	13.0	24.0
M1 T15	**Archaic**	**F**	**old**	**3.2**	**27.4**	**-12.8**	**10.0**	**24.8**
M1 T16b	**Archaic**	**M?**	**mid?**	**3.9**	**26.1**	**-13.4**	**9.5**	**25.0**
M1 T18c2	**Archaic**	**U**	**U**	**3.9**	**45.3**	**-14.0**	**13.6**	**21.8**
M1 T19c1	**Archaic**	**M**	**young**	**3.7**	**32.3**	**-12.3**	**10.1**	**25.0**
M1 T22c5	**Archaic**	**F**	**mid**	**-**	**-**	**-**	**-**	**-**
M1 T23c3	**Archaic**	**M?**	**young-mid**	**-**	**-**	**-**	**-**	**-**
M1 T23c12	**Archaic**	**F?**	**young**	**-**	**-**	**-**	**-**	**-**
MI T23c13	Archaic	F	young	3.5	45.6	-13.8	15.2	25.5
M1 T27c5	**Archaic**	**M**	**young**	**4.0**	**28.5**	**-12.8**	**8.5**	**23.9**
M1 T27c11	**Archaic**	**M?**	**young-mid**	**-**	**-**	**-**	**-**	**-**
M1 T28c12	**Archaic**	**M?**	**U**	**-**	**-**	**-**	**-**	**-**
M1-6 T19	**Archaic**	**U**	**U**	**3.7**	**28.1**	**-12.8**	**8.8**	**23.9**
Az115 Museo C4	**Formative**	**M?**	**U**	**-**	**-**	**-**	**-**	**-**
Az115 Museo C7	**Formative**	**U**	**U**	**3.8**	**42.2**	**-16.3**	**13.0**	**16.0**
AZ115 S/R1	Formative	U	U	3.3	43.8	-15.1	15.5	15.3
AZ115 T3b (BN294)	Formative	M?	mid	3.3	40.4	-15.8	14.3	17.9
Az115 T5	Formative	M	young-mid	3.3	41.7	-14.8	15.0	16.8
AZ115 T8	Formative	F	mid	3.5	44.3	-13.1	14.9	15.5
AZ115 T9	Formative	F?	young-mid	3.2	38.3	-15.1	13.8	15.4
AZ115 T11	Formative	F	mid	3.6	47.0	-15.6	15.3	15.9

Az115 T16a	Formative	M	young	3.3	41.3	-13.4	14.7	21.3
Az115 T16b	**Formative**	**M**	**mid**	**-**	**-**	**-**	**-**	**-**
Az115 T17a	**Formative**	**M**	**mid-old**	**-**	**-**	**-**	**-**	**-**
AZ115 T17b	Formative	F	mid	3.3	42.2	-14.9	14.8	17.1
AZ115 T18	Formative	M	mid	3.4	44.4	-14.3	15.5	16.5
AZ115 T19	Formative	M	mid	3.6	44.7	-15.2	14.7	17.3
AZ115 T21	Formative	F	mid	3.4	45.7	-14.2	15.6	14.7
AZ115 T22	Formative	M	young-mid	3.4	44.2	-11.9	15.3	20.0
AZ115 T25	Formative	F	young-mid	3.3	41.7	-14.4	14.7	17.7
AZ115 T26	Formative	M	young-mid	3.5	44.3	-13.1	14.9	15.5
AZ14 ent1	Formative	M	U	3.6	32.8	-12.7	10.7	25.0
AZ14 TX	Formative	F?	young	3.5	38.3	-18.4	12.7	16.7
AZ14 T1	Formative	M	mid	3.3	39.8	-17.0	14.1	17.4
AZ14 T1 F15	Formative	F	young	3.3	42.8	-17.0	15.1	17.6
AZ14 T7	Formative	F	old	3.4	44.5	-18.3	15.6	13.6
AZ14 T10	Formative	M	young-mid	3.2	42.5	-11.8	15.7	25.5
AZ14 T14	Formative	F	young	3.6	42.2	-17.0	13.8	17.8
Az14 T59	**Formative**	**M**	**young**	**-**	**-**	**-**	**-**	**-**
Az14 T64c	**Formative**	**M**	**U**	**-**	**-**	**-**	**-**	**-**
Az14 T66	**Formative**	**M**	**U**	**-**	**-**	**-**	**-**	**-**
Az14 T69	**Formative**	**M**	**mid**	**-**	**-**	**-**	**-**	**-**
AZ14 T76b	Formative	M?	young	3.5	43.3	-18.2	15.5	13.7
Az6 MCA3	**Middle Horizon**	**F**	**mid**	**-**	**-**	**-**	**-**	**-**
Az6 T6	**Middle Horizon**	**F**	**young**	**-**	**-**	**-**	**-**	**-**
Az6 T19	Middle Horizon	F	young	3.3	42.1	-10.2	14.7	25.7
Az6 T22 G1/1	**Middle Horizon**	**F**	**mid-old**	**-**	**-**	**-**	**-**	**-**
Az6 T25 H1/1	**Middle Horizon**	**M**	**young**	**-**	**-**	**-**	**-**	**-**

Az6 T26 H1/2	**Middle Horizon**	**F**	**young-mid**	**-**	**-**	**-**	**-**	**-**
Az6 T36 J2/1	Middle Horizon	M	young	3.4	40.9	-11.2	14.2	21.1
Az6 T41b	Middle Horizon	M	mid	3.3	42.7	-11.4	14.9	20.4
Az6 T48 K1/2	**Middle Horizon**	**F**	**U**	**-**	**-**	**-**	**-**	**-**
Az6 T71 M5/2	Middle Horizon	M	young	3.4	43.0	-11.4	14.8	15.9
Az6 T116 R3/2	Middle Horizon	M	mid	3.4	42.0	-11.1	14.6	21.6
Az141 Des02	Middle Horizon	F	mid	3.5	38.6	-13.4	12.8	23.9
Az141 T22	Middle Horizon	M	mid	3.2	37.4	-12.2	13.5	14.6
Az141 T23	Middle Horizon	U	U	3.6	44.1	-11.3	14.4	18.2
Az141 T26	**Middle Horizon**	**M**	**young**	**-**	**-**	**-**	**-**	**-**
Az141 T33	Middle Horizon	M	mid-old	3.2	33.2	-12.3	12.0	11.7
Az141 T36	**Middle Horizon**	**M**	**young**	**-**	**-**	**-**	**-**	**-**
Az141 T37	**Middle Horizon**	**F**	**mid**	**-**	**-**	**-**	**-**	**-**
Az141 T52	Middle Horizon	M	young-mid	3.4	41.1	-11.3	14.3	19.2
Az141 T53	**Middle Horizon**	**M**	**young**	**-**	**-**	**-**	**-**	**-**
Az11 T3	Late-Int	F	old	3.4	47.0	-14.9	15.9	10.7
Az11 T7a	**Late-Int**	**M**	**young-mid**	**-**	**-**	**-**	**-**	**-**
Az11 T7	Late-Int	F	mid	3.6	43.3	-11.8	14.1	17.6
Az11 Sec T8	Late-Int	F	mid-old	3.4	42.3	-11.1	14.7	11.6
Az11 T16	Late-Int	M	mid	3.4	42.6	-17.8	14.6	11.8
Az8 T5b	Late-Int	F	mid	3.3	42.5	-10.8	15.0	21.2
Az8 T7a	Late-Int	M?	young	3.4	41.2	-12.0	14.0	20.9
Az8 T7b	**Late-Int**	**M**	**young-mid**	**-**	**-**	**-**	**-**	**-**
Az8 T9	Late-Int	F	young	3.5	44.3	-10.6	14.6	21.6
Az8 T13	Late-Int	M	young	3.4	43.5	-11.3	14.9	20.4
Az8 T19	**Late-Int**	**F**	**mid**	**-**	**-**	**-**	**-**	**-**
Az8 T23	**Late-Int**	**F**	**mid-old**	**-**	**-**	**-**	**-**	**-**

Az8 T24	Late-Int	F	mid-old	3.2	41.6	-12.1	15.1	19.8
Az8 T25	Late-Int	M	young-mid	3.5	39.7	-11.8	13.3	20.4
Az8 T30	Late-Int	F	young	3.5	44.8	-11.6	15.1	20.7
Az8 T31	Late-Int	F	young	3.4	42.2	-12.2	14.7	17.4
Az8 T35	Late-Int	M	young	3.5	44.0	-11.2	14.5	20.3
Az8 T38	Late-Int	F	young	3.4	41.6	-12.2	14.3	20.1
Az8 T40	Late-Int	F	young-mid	3.4	43.7	-10.7	15.1	15.2
Az8 T41	**Late-Int**	**F**	**young-mid**	**-**	**-**	**-**	**-**	**-**
Az8 T42	Late-Int	M	young	3.6	44.3	-15.5	14.5	17.5
Az8 T43	**Late-Int**	**M**	**young**	**-**	**-**	**-**	**-**	**-**
Cam8 TA1	Late	F	mid	3.3	43.3	-12.1	15.1	24.0
Cam8 TA2	Late	M	mid-old	3.4	43.5	-11.9	15.0	22.7
Cam8 TA4	Late	M	old	3.3	42.7	-11.8	15.3	22.9
Cam8 TUW1	Late	M	old	3.3	41.2	-11.6	14.7	21.0
Cam8 T3	Late	F?	mid	3.2	40.7	-12.2	14.6	25.2
Cam8 T4 cuad F4	Late	M	young-mid	3.4	43.6	-11.9	15.0	25.1
Cam8 T6	Late	F	young-mid	3.4	42.2	-12.5	14.7	23.8
Cam8 T9	Late	f?	young	3.4	39.7	-13.1	13.7	23.7
Cam8 T15	Late	F	old	3.3	40.6	-12.5	14.4	20.5
Cam8 T19	Late	F?	mid-old	3.3	41.3	-12.1	14.5	23.4
Cam9 T2	Late	F?	young?	3.3	41.5	-11.0	14.6	24.2
Cam9 T8	Late	M	mid	3.3	44.1	-10.9	15.4	24.2
Cam9 T12	Late	F	mid	3.4	43.2	-11.1	15.0	23.0
Cam9 T13	Late	M	old?	3.4	43.7	-10.7	15.1	23.5
Cam9 T14	Late	M	young	3.7	43.0	-11.7	13.6	24.9
Cam9 T15	Late	U	U	3.5	44.2	-10.5	14.7	24.8
Cam9 T16	Late	F?	mid	3.3	42.4	-11.7	14.9	24.3

Cam9 T19	Late	F	young	3.3	43.2	-11.0	15.3	23.8
Cam9 T23	Late	U	young	3.4	43.5	-10.3	15.1	24.6
Cam9 T32c2	Late	M	young?	3.5	43.4	-11.3	14.6	24.8
Cam9 T33	Late	M	mid	3.4	43.4	-10.4	14.9	24.6
Cam9 T54c2	Late	F?	young?	3.3	42.8	-11.8	15.0	24.0
Cam9 T57	Late	U	U	3.4	43.3	-9.9	14.7	24.6
Cam9 T59	Late	F	U	3.2	42.0	-12.1	15.4	24.8
Cam9 T61	Late	F?	mid	3.4	41.3	-10.5	14.3	22.0

Supplemetary table 1: Giving full isotopic results including collagen quality indicators for all analysed individuals. Skeletal sex information was undertaken using Buikstra & Ubelaker [1]. F = female, M= male, U= unknown. Age categories are derived from the scoring of the pubic symphysis [2] and auricular surface [3], with epiphyseal fusion taken into account in the case of young adults (Buikstra and Ubelaker, 1994). All isotopic measurements were taken in duplicate, data given here is the mean value, the difference between all repeat measurements was used to calculate the technical error of measurement on isotopic ratios (TEM $\delta^{13}C$ = 0.2‰; $\delta^{15}N$ = 0.14‰).

Individuals highlighted in bold have failed collagen quality checks/ did not give a collagen yield (indicated by -) and are therefore not included in-text. Collagen was considered to be of good quality if the: C/N ratio = 2.9 - 3.6 and 35-50% carbon and 11-16% nitrogen, as per Durham University Archaeology lab standards (based on [4])

References:

1. Buikstra JE, Ubelaker DH (1994) Standards for data collection from human skeletal remains.
2. Brooks S, Suchey JM (1990) Skeletal age determination based on the os pubis: a comparison of the Acsádi-Nemeskéri and Suchey-Brooks methods. Human evolution 5: 227-238.
3. Lovejoy CO, Meindl RS, Pryzbeck TR, Mensforth RP (1985) Chronological metamorphosis of the auricular surface of the ilium: a new method for the determination of adult skeletal age at death. American Journal of Physical Anthropology 68: 15-28.

4. Ambrose SH (1990) Preparation and characterization of bone and tooth collagen for isotopic analysis. Journal of Archaeological Science 17: 431-451.

Phase	C_3 input				C_4 input				Terrestrial meat input				Marine input			
	+1.5 both C & N	**-1.5 both C & N**	**-1.5 C, +1.5 N**	**+1.5 C, -1.5 N**	**+1.5 both C & N**	**-1.5 both C & N**	**-1.5 C, +1.5 N**	**+1.5 C, -1.5 N**	**+1.5 both C & N**	**-1.5 both C & N**	**-1.5 C, +1.5 N**	**+1.5 C, -1.5 N**	**+1.5 both C & N**	**-1.5 both C & N**	**-1.5 C, +1.5 N**	**+1.5 C, -1.5 N**
Archaic	34 ± 13	33 ± 10	32 ± 11	34 ± 11	10 ± 6	8 ± 5	12 ± 6	8 ± 5	21 ± 9	13 ± 6	18 ± 7	15 ± 7	35 ± 7	46 ± 6	38 ± 7	43 ± 6
Formative	32 ± 22	28 ± 19	31 ± 20	29 ± 20	20± 14	29 ± 17	32 ± 17	19 ± 13	36 ± 20	24 ± 16	25 ± 16	34 ± 19	12 ± 9	19 ± 11	12 ± 9	18 ± 10
Middle Horizon	27 ± 17	13 ± 10	15 ± 11	26 ± 17	35 ± 13	57 ± 12	60 ± 11	32 ± 14	18 ± 12	9 ± 6	9 ± 7	17 ± 11	20 ± 13	21 ± 12	16 ± 11	25 ± 13
Late-Int	30 ± 20	21 ± 16	22 ± 16	29 ± 19	30 ± 16	44 ± 17	48 ± 17	26 ± 15	25 ± 16	14 ± 11	16 ± 11	23 ± 15	15 ± 11	21 ± 12	14 ± 12	22 ± 12
Late	23 ± 15	10 ± 8	11 ± 9	23 ± 14	30 ± 12	46 ± 11	55 ± 10	25 ± 12	16 ± 10	5 ± 4	7 ± 5	11 ± 8	31 ± 9	39 ± 8	27 ± 8	41 ± 7

Supplementary Table 2: Reconstructed % contributions to diet by phase in alternative models where food source inputs values have been changed by ±1.5‰

Phase	C_3 input			C_4 input			Terrestrial meat input			Marine input		
	No priors	**+1 offset**	**-1 offset**	**No priors**	**+1 offset**	**-1 offset**	**No priors**	**+1 offset**	**-1 offset**	**No priors**	**+1 offset**	**-1 offset**
Archaic	17 ± 13	34 ± 12	34 ± 10	28 ± 14	10 ± 6	8 ± 5	11± 8	19 ± 8	14 ± 7	44 ± 13	37 ± 7	44 ± 6
Formative	30 ± 21	32 ± 21	29 ± 19	24 ± 16	21 ± 14	27 ± 16	29 ± 18	34 ± 19	26 ± 17	16 ± 12	13 ± 9	18 ± 11
Middle Horizon	19 ± 14	25 ± 16	15 ± 11	43 ± 16	42 ± 12	53 ± 12	12 ± 9	17 ± 11	10 ± 7	26 ± 18	20 ± 13	22 ± 13
Late-Intermediate	25 ± 18	29 ± 19	22 ± 16	35 ± 17	32 ± 16	42 ± 17	19 ± 13	23 ± 15	16 ± 12	21 ± 15	16 ± 11	20 ±11
Late	15 ± 11	21 ± 14	11 ± 9	35 ± 14	33 ± 12	45 ± 11	9 ± 7	13 ± 9	6 ± 5	41 ± 13	33 ± 9	38 ± 8

Supplementary Table 3: Reconstructed % inputs to diet when a) prior assumptions regarding protein carbon contribution are removed and b) diet-collagen offsets are changed by 1‰.

Phase	C_3 input	C_4 input	Terrestrial meat input	Marine input
Archaic	n/a	n/a	n/a	n/a
Formative	n/a	n/a	n/a	n/a
Middle Horizon	21 ± 14	47 ± 13	13 ± 9	19 ± 13
Late-Intermediate	27 ± 18	37 ± 17	20 ± 13	16 ± 12
Late	17 ± 12	42 ± 13	10 ± 7	31 ± 10

Supplementary Table 4: Reconstructed % contributions to diet when guano fertilized C_4 plants are considered a possibility. Note that this model is applied only to Middle Period onwards as archaeological evidence for fertilization only appears from the Middle Period.